Reentry Survivability Analysis of the Extreme Ultraviolet Explorer Satellite (EUVE)

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An artist's rendition of the Extreme Ultraviolet Explorer (EUVE) satellite in its on - orbit configuration

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EXECUTIVE SUMMARY

A reentry survivability analysis of components of the Extreme Ultraviolet Explorer (EUVE) spacecraft was performed to assess the risk of significant debris resulting from an uncontrolled reentry. EUVE does not have a propulsion system so a controlled reentry is impossible. Flight dynamics analysis shows that EUVE's orbit is decaying quickly and without a reboost by the Shuttle it could reenter earth's atmosphere as early as October 1, 2001. This survivability analysis was performed in accordance with NASA Policy Directive, NPD 8710.3, "NASA Policy For Limiting Orbital Debris Generation" and NASA Safety Standard, NSS 1740.14, "Guidelines and Assessment Procedures for Limiting Orbital Debris". This analysis utilized Debris Analysis Software (DAS) Release 1.0, supplied through NASA's Orbital Debris Program Office at the Johnson Space Center (JSC). JSC is the NASA Lead Center for orbital debris research. This document describes the analysis method used for the breakup of EUVE, the assumptions and manipulations employed to model various resultant fragments and provides an estimate of the reentry debris casualty area from those components predicted to survive reentry. More than 40 objects were modeled, with 18 predicted to survive creating a total debris casualty area of 12.41 square meters. This exceeds the NSS 1740.14 Guideline number 7 upper limit of 8 square meters and represents a risk of 1 in 5400 for causing a casualty within the ground track for EUVE which has a 28.5 degree orbital inclination.

1. INTRODUCTION

The NASA Goddard Space Flight Center (GSFC) Extreme Ultraviolet Explorer spacecraft (EUVE) was launched on June 7, 1992, into a 528 kilometer (km) low earth orbit inclined at 28.5 degrees, aboard a Delta II rocket from Cape Canaveral [reference 4]. Figure 1 from reference 6, shows an artist's impression of the EUVE spacecraft in orbital configuration with the major components identified. Additional figures in Sections 2 and 3 provide expanded views of the structure showing the relationship between the major components. The spacecraft is a free flying orbital platform equipped with four telescopes for detecting extreme ultraviolet radiation. The three smaller grazing incidence, scanning telescopes are mounted together in a coplanar configuration along the spacecraft's minor axis. The fourth and largest telescope is an extreme ultraviolet (EUV) spectrometer/deep survey instrument mounted parallel to the spacecraft's major axis. The original intention was to launch EUVE with the Shuttle and to also do on-orbit servicing and eventual retrieval using the Shuttle, so EUVE is equipped with the required hard points such as grapples and trunnions.

At launch, the EUVE spacecraft had a mass of 3243 kilograms (kg) [reference 3] and external dimensions minus the solar panels of approximately 1.9 meters (m) in diameter by 3.9 m long [reference 8]. There is no propulsion unit and the three-axis attitude control is by reaction wheels and magnetic torquer rods, not thrusters, thus there is no propellant and the mass of EUVE should still be 3243 kg. There are no pressurized vessels, propellant tanks or other potential sources of explosion except for the batteries. The EUVE is equipped with three nickel cadmium batteries, each consisting of 22 individual cells. The cells were pressurized to 65 psig (4.4 atmospheres) during manufacture and can reach 80 psig during heavy use [reference 19], so they could present a potential explosion hazard, once the spacecraft structure begins to break up.

The basic methodology for this analysis follows the guidelines in NASA Safety Standard, NSS 1740.14, "Guidelines and Assessment Procedures for Limiting Orbital Debris", in particular Guideline number 7, "Survival of Debris from the Post Mission Disposal Atmospheric Reentry Option". For this analysis, the intact EUVE spacecraft was assumed to break up at an altitude of 78 km, which has been determined to be the approximate altitude at which most spacecraft structures begin to disintegrate [reference 9]. Below this altitude, various components and subcomponents were assumed to become free falling and were modeled individually. Components inside boxes were not modeled until the box wall was known to have demised. A detailed description of the modeling approach can be found in Section 2, Methods of Analysis.

The calculation of the demise altitudes and debris casualty area for the various items modeled was performed using NASA Orbital Debris Analysis Software (DAS) Version 1.0, developed by the Orbital Debris Program Office at the Johnson Space Center [reference 2]. DAS is an acceptable analysis tool per the NASA Safety Standard. More sophisticated, higher fidelity tools such as the ORSAT software are available to the JSC debris analysis group. Close correlation between the DAS results for EUVE and ORSAT calculations for similar objects on the Compton Gamma Ray Observatory (CGRO) [reference 17], provides confidence in the DAS results.

The Orbital Debris Program Office at JSC is part of the Office of Space Flight, and is responsible per paragraph 5.d of NASA Policy Directive, NPD 8710.3, "NASA Policy For Limiting Orbital Debris Generation" for "reviewing end-of-life assessments of programs that were operational prior to April 5, 1993, to assess environmental impact" [reference 15].

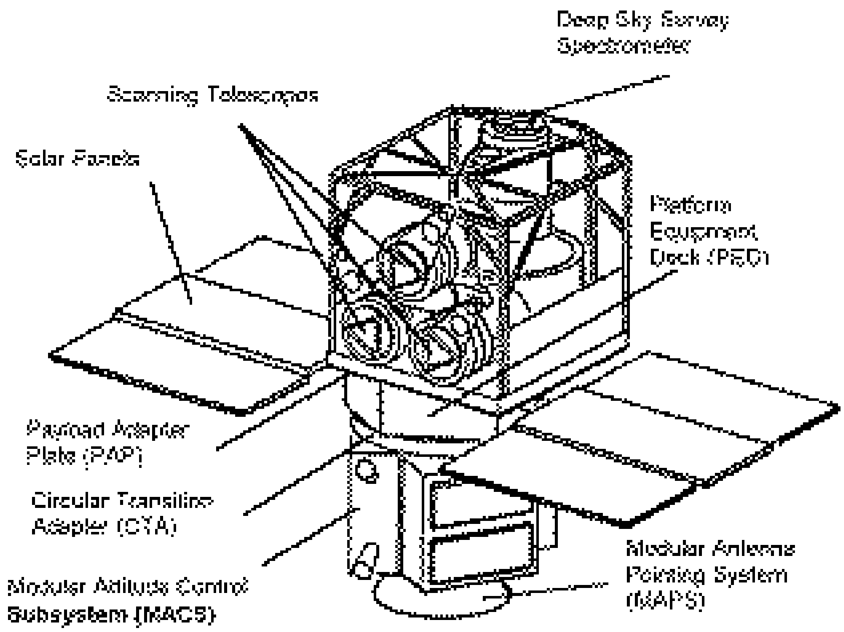

Figure 1. The Extreme Ultraviolet Explore Spacecraft in its Orbital Configuration [reference 6]

2. METHOD OF ANALYSIS

2.1 NASA REQUIREMENTS

2.1.1 NPD 8710.3, "NASA POLICY FOR LIMITING ORBITAL DEBRIS GENERATION"

NPD 8710.3 states that it is NASA policy to, "Conduct a formal assessment in accordance with NSS 1740.14, on each NASA program/project". However, the NPD goes on to say in Section 2. APPLICABILITY, "Programs that were operational prior to April 5, 1993 should limit the assessment to debris-limiting options at the end of life". This statement applies to EUVE as it was operational prior to this date and this study fulfills the NPD requirements.

2.1.2 NSS 1740.14, "GUIDELINES AND ASSESSMENT PROCEDURES FOR LIMITING ORBITAL DEBRIS"

Section 7 of NSS 1740.14 contains the following Guideline:

> 7-1 *Limit the risk of human casualty:* If a space structure is to be disposed of by uncontrolled reentry into the earth's atmosphere, the total debris casualty area for components and structural fragments surviving reentry will not exceed 8 m^2. The total debris casualty area is a function of the number and size of components surviving reentry and of the average size of a standing individual.

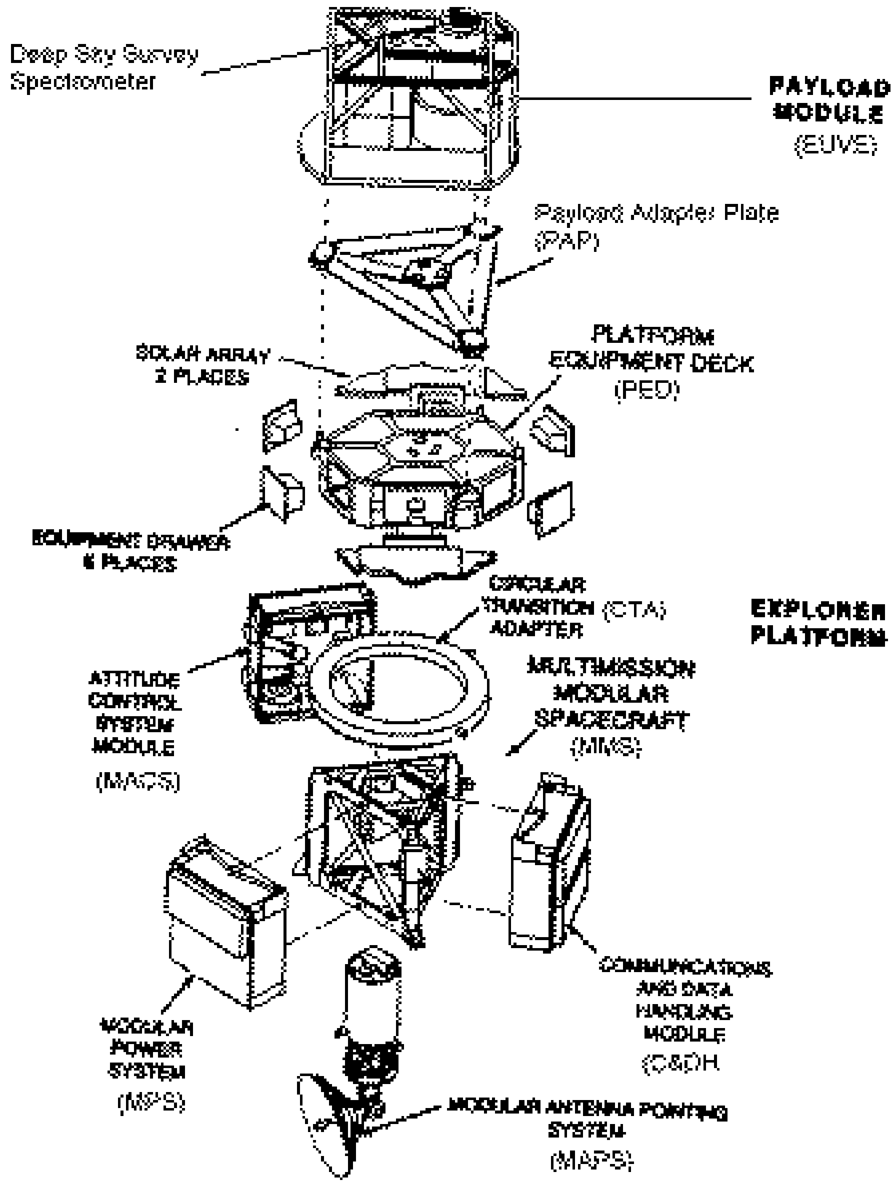

Figure 2. An exploded view of the EUVE spacecraft showing its major components [reference 16]

In the Method to Assess Compliance with the Guidelines for Section 7, it is stated,

> 3. If the parent body is larger than 0.5 m in any dimension and consists of multiple components, it will break up into components of significant size during reentry. Each of these components must then be evaluated separately. The design of the structure must be reviewed and all components that are larger than 0.25 m in any dimension must be identified.

The Method description goes on to state that all objects identified as exceeding the dimensional requirement of 0.25 m must be modeled for reentry debris.

2.2 NASA ORBITAL DEBRIS ANALYSIS SOFTWARE (DAS) VERSION 1.0

DAS is a DOS based program that is configured to follow the structure of NSS 1740.14. In particular it is divided into options that correspond to the Guidelines sections in the NSS. This analysis was performed using the Guideline 7 option for uncontrolled reentry debris.

Figure 2 shows an exploded view of the complete EUVE spacecraft, which should be helpful in understanding references to spacecraft components in the next sections.

DAS allows the modeling of objects as spheres, cylinders, boxes or plates only. This means that actual spacecraft fragments, which are rarely uniform in shape, require manipulation to be modeled as the closest equivalent to one of these shape options. Also, the NSS encourages the modeling of objects as either spheres or cylinders because these shapes are modeled most accurately by the software, so this was done for EUVE components whenever practical. In addition, DAS cannot directly model the wall thickness of hollow objects, such as the Modular Power Subsystem (MPS) box on EUVE. Manipulation of material properties can be used to compensate for this limitation, in accordance with a procedure recommended by the experts at JSC. The results of these various compensations and manipulations are shown in Table 1 but the underlying philosophies and methods are described in detail in the following sections.

2.2.1 MODELING OF OBJECTS – *SHAPE*

As stated in 2.2 it was necessary to perform various manipulations of the dimensions of actual objects in order to convert them to a close equivalent in one of the shapes allowed by DAS. The following paragraphs describe examples of these manipulations and the rationale behind them.

2.2.1.1 Tubes and Rings

The Circular Transition Adapter (CTA) is a large diameter (~ 1.7 m) aluminum annulus or ring with a proportionately very thin rim (~ 0.2 m square cross-section). In order to model this object in DAS, manipulation was required. It was decided to model the CTA as a cylinder using the actual height (thickness) of the ring, and the known mass (from the mass properties analysis) but with a modified diameter. The diameter of the cylinder was calculated to have the same total surface area on that face as the annulus. This ensured that the drag experienced while descending with the circular face foremost would be essentially correct, although the drag on the other axis would be reduced slightly. The rims of the reaction wheels are also rings and were modeled in a similar way. This is considered a conservative approach because the slight reduction in drag in one axis tends to increase the likelihood the object will survive reentry. In section 7 of the NSS it is stated:

"A necessary and sufficient condition for a structure to survive reentry is
$$H < M \times h_a / A_s$$"

Where

- H = the heat load per unit area experienced by a reentering space structure (J/m^2)
- M = the component mass (kg)
- h_a = the specific heat of ablation of the nominal material (J/kg)
- A_s = the surface area of the component (m^2)

Therefore, the probability of surviving reentry is inversely proportional to surface area.

2.2.1.2 Boxes

Although boxes can be modeled directly in DAS, for this analysis they were usually converted to equivalent cylinders. The thickness (height) and cross-sectional area of the box were maintained at their nominal values but the length and width of the box were converted to the diameter necessary to generate the required cross-sectional area. As an example, the MPS box, which is 1.19 m square by 0.46 m thick [reference 6], was modeled as a cylinder 1.35 m in diameter and 0.46 m long.

2.2.1.3 Complex Structures

Various major components of EUVE are highly irregular in shape or do not lend themselves easily to conversion to cylinders or spheres; examples are various aluminum beams that are either hollow, L-shaped or U-shaped in cross-section. The EUVE instrument deck grapple fitting is a cast trapezoid plate, strengthened with webs and perforated with a number of holes. The instrument equipment support panel is a large, machined, "waffle" plate made of aluminum, which as a result of the machining has a mass much lower than a solid plate of the same external dimensions. Each of these complex shapes had to be manipulated individually using a variety of techniques, including material density modification (see 2.2.2). The modification techniques sought to preserve key features of the objects such as surface area along the major axis. In many instances, manipulation had to be based on best engineering judgment.

2.2.2 MODELING OF OBJECTS – *MATERIAL PROPERTIES*

DAS contains a materials database of the key parameters for most of the materials commonly used in spacecraft construction. These material properties produce accurate results when used for solid objects but as mentioned previously, DAS cannot model the wall thickness of hollow objects such as boxes, so a simple modification of material properties is necessary to produce satisfactory results. The basic approach is to create a "synthetic" material that has a modified density, specific heat and heat of fusion but other parameters identical to the parent material. The synthetic material density is simply the known or estimated mass of the object divided by its modeled volume. For example, the MPS box which has an aluminum outer shell, has a mass of 281 kg [reference 3] and a volume of 0.65 m^3 giving a synthetic material density of 432 kg / m^3, compared to the actual density of aluminum of 2800 kg / m^3. The corresponding values for specific heat and heat of fusion are found by multiplying their nominal values by the ratio of the actual to synthetic densities, 432/2800 or 0.15 in this example. The Communications and Data Handling (C&DH) and Modular Attitude Control Subsystem (MACS) boxes are almost identical to the MPS box in dimensions but have different masses so they have their own corresponding synthetic material properties. Material properties for all the materials used in this study are shown in Table 1.

The MPS box on EUVE is very similar in dimensions and mass to the MPS box on CGRO. The demise altitude for the CGRO MPS box calculated using the ORSAT software configured for the wall thickness of the box, was 71.7 km [reference 17]. The demise altitude for the EUVE box calculated by inputting similar initial conditions into DAS and using synthetic material compensation was 71.5 km, demonstrating the effectiveness of this compensation method. Performing the same calculation in DAS without the synthetic material modification shows the box surviving intact to the ground. The actual exterior panels of the MPS box are relatively insubstantial, clad aluminum honeycomb that clearly would not survive reentry.

<u>Note.</u> The final calculated demise altitude for the EUVE MPS box shown in this report is 60.9 km (not 71.5 km as mentioned above). For the CGRO analysis, the MPS box was assumed to free-fall as soon as the parent spacecraft demised at 78 km. Due to differences in spacecraft construction, the MPS box on EUVE was not assumed to be free-falling until the demise of the Multi Mission Spacecraft (MMS) structure at 67.48 km, hence the lower demise altitude for the MPS box.

2.2.3 MODELING OF OBJECTS – *MASS*

The Final Mass Properties Report for EUVE [reference 3] contains the masses of all major components except the solar arrays, many sub-components and even small parts such as the grapples and torquer bars. However, the masses of many of the items modeled for this analysis had to be calculated or estimated. In two instances, actual representative hardware was available for weighing and was used to validate the estimation methodology. The hardware was a corner beam and bracket for the Module Support Structure (MSS). The complexity of many of the plates and machined forgings made an accurate determination of their mass unacceptably time-consuming. Complex objects such as the “waffle” equipment support panels of the EUVE instrument deck were estimated by using “fill ratio” concept. The fill ratio is the estimated proportion of the actual volume occupied by solid material, divided by the volume of the total dimensional envelope of the object. For example, examination of the instrument support panels show them to be heavily machined so that their overall thickness of 0.75 inches is reduced to 0.10 inches over most of their area. Modeling of these panels assumed a fill ratio of 20%, which allows for the presence of vertical ribs in the structure that are at the full material width. The instrument support panels were modeled with a mass of 11.11 kg instead of the 55.55 kg a solid panel would weigh.

Table 1 Materials Database Used For Reentry Calculations

Material Name	Material Density (kg/m^3)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)	Heat of Fusion (J/kg)	Heat of Oxidation (J/kg-O2)	Melt Temp (K)	Synthetic Material Based on
Al 2024-T3	2803.2	972.0	120	386116	34910934	856	---
Al 2024-T8xx	2803.2	972.7	155	386116	34910934	856	---
Al 2219-T8xx	2812.8	862.5	120	386116	34910934	856	---
Al 6061-T6	2700.0	896.0	167	386116	34910934	859	---
Al 7075-T735x	2810.0	960.0	155	386116	34910934	750	---
Copper	8938.0	430.7	396	205932	9832002	1356	---
Iron	7860.0	440.0	80	247104	16816980	1809	---
Molybdenum	10220.0	255.0	138	286320	17386300	2890	---
Steel AISI 304L	8000.0	500.0	16	286098	16816980	1698	---
Titanium	4437.0	805.2	7	393559	32480264	1943	---
BATpk	2529.4	158.1	16	90456	16816980	1698	Steel AISI 304L
CBP	6483.0	161.8	138	181625	17386300	2890	Molybdenum
CDH	307.7	106.8	155	42386	34910934	856	Al 2024-T8xx
COVR	840.4	278.9	167	120187	34910934	859	Al 6061-T6
CTA	1054.9	823.5	120	144801	34910934	856	Al 2219-T8xx
ESP	10.0	3.3	167	1432	34910934	859	Al 6061-T6
FRAME	15.7	5.2	167	2248	34910934	859	Al 6061-T6
Grapple	803.4	266.6	167	114884	34910934	859	Al 6061-T6
HNG	4973.3	310.8	16	177857	16816980	1698	Steel AISI 304L
Inst	243.3	74.6	120	33397	34910934	856	Al 2219-T8xx
MACS	299.5	103.9	155	41254	34910934	856	Al 2024-T8xx
MAPS	79.5	26.4	167	11370	34910934	859	Al 2024-T8xx
MMS	385.4	133.7	155	53080	34910934	856	Al 2024-T8xx
MMSCB	224.3	76.6	155	30815	34910934	750	Al 7075-T735x
MMSCR	9.1	3.0	167	1299	34910934	859	Al 6061-T6
MMSTB	386.9	132.2	155	53166	34910934	750	Al 7075-T735x
MMSTS	411.6	142.7	120	56692	34910934	856	Al 2024-T3
MPS	431.6	149.8	155	59450	34910934	856	Al 2024-T8xx
MRSB	816.4	283.1	120	112457	34910934	856	Al 2024-T3
MRSLF	676.0	234.4	120	93109	34910934	856	Al 2024-T3
PAP	344.1	114.2	167	49209	34910934	859	Al 6061-T6
PAPCC	76.2	25.3	167	10903	34910934	859	Al 6061-T6
PAPTBL	671.0	222.7	167	95955	34910934	859	Al 6061-T6
PAPTBS	672.6	223.2	167	96184	34910934	859	Al 6061-T6
PAPV	981.8	325.8	167	140396	34910934	859	Al 6061-T6
PED	592.0	196.5	167	84662	34910934	859	Al 6061-T6
PEDCA	451.9	150.0	167	64627	34910934	859	Al 6061-T6
PEDCH	323.1	107.2	167	46207	34910934	859	Al 6061-T6
Pmod	650.5	215.9	167	93024	34910934	859	Al 6061-T6
RWA	815.5	250.1	120	111951	34910934	856	Al 2219-T8xx
SADA	1690.2	306.7	7	149916	32480264	1943	Titanium
SAIF	610.9	110.9	7	54183	32480264	1943	Titanium
SCAN	494.9	151.8	120	67937	34910934	856	Al 2219-T8xx
SPEC	236.8	72.6	120	32510	34910934	856	Al 2219-T8xx
TorCu	7137.3	343.9	396	164443	9832002	1356	Copper

Note. Materials for this table were identified from references 1, 5, 7, 8, 10, 12, 18 and 19. Material properties were generated from values in the DAS database, augmented from reference 11

2.3 ASSUMPTIONS

2.3.1 INITIAL CONDITIONS

The EUVE spacecraft was assumed to begin to break up at an altitude of 78 km, the default value for DAS and as previously mentioned the accepted value for the typical initial breakup altitude for reentering objects. The reentry trajectory is preprogrammed into DAS.

2.3.2 BREAKUP SEQUENCE

The initial breakup at 78 km is assumed to consist of separation into the largest cohesive component parts. These are (see Figures 1 and 2):

- The Solar Arrays
- The Platform Equipment Deck (PED)
- The Multi-mission Modular Spacecraft (MMS)
- The Modular Antenna Pointing System (MAPS)
- The EUVE Payload

The solar panels were assumed to be torn off at 78 km and to demise almost immediately. Analysis of the information available on the panels themselves showed no massive (heavy) objects that exceeded the 0.25m dimensional limit. The main hinges for the panels are large and made of titanium but they are attached to the solar panel drive units, which were modeled as part of the break-up of the PED. Smaller titanium hinges between individual panels were below the 0.25 m dimensional limit.

The PED, MMS, MAPS and EUVE payload were modeled as cylinders made with synthetic materials based on the known exterior surface materials and the masses for each component. This first DAS run generated demise altitudes for each of these components that were then used as break-up altitudes for runs to analyze the behavior of their respective sub-components. In cases where these sub-components in turn contained other objects of interest, this process was repeated down to the next level. As an example, the four reaction wheel assemblies (RWAs) located in the Modular Attitude Control Subsystem (MACS), each contain an aluminum momentum wheel with a steel rim. The MACS is a box attached to the MMS. So the modeling for the break-up of RWAs consisted of a first run to determine the demise altitude for the MMS, a second run to determine the demise altitude for the MACS, a third run to determine the demise altitude for the RWA and a fourth to analyze the steel reaction wheel rim (which survived).

The order in which the structure was modeled to break-up was somewhat arbitrary. Every attempt was made to follow a logical progression but it is simply not possible to predict if two objects such as the PED and the MMS would separate as somewhat intact objects or if the process would cause more massive disintegration. In other cases, parts of one structure also formed parts of another. For instance, the PED module front panels also form part of the exterior of the PED structure itself, should these front panels also demise when the PED structure was shown to demise? A conservative choice was made and the complete PED module was modeled as a separate structure that only began free-falling with the demise of the PED. Objects such as the CTA and the grapples, which are made of a number of sub-components bolted together, were usually modeled as single pieces. Box beams made from “C” section extrusions and flat plates adhesively bonded together were also modeled intact. This is a conservative approach because larger objects have a higher probability of survival than their smaller sub-components.

2.3.3 OBJECT SELECTION

The EUVE structure consists of hundreds of major structural components and thousands of smaller ones. It is not practical to model all objects over 0.25 m in length so some assumptions were necessary to focus the effort on those with the greatest chance of surviving reentry. The most common material found on EUVE was aluminum alloy. Experimentation with some examples of large aluminum components showed that they have a small probability of survival. Therefore only the largest or heaviest aluminum objects were generally selected for analysis. Aluminum objects were selected to represent most of the dominant shapes (box beams, U and L sections, disks etc), with the largest or heaviest example then considered representative of all similar objects in the system or sub-system. In other words, if the beam that was analyzed demised, then all beams of similar and smaller size and weight would also be assumed to demise.

The other class of objects selected was those consisting of dense materials with high melting points, which in EUVE were titanium, stainless steel and molybdenum. This report provides results for all objects that are known to meet or exceed the 0.25 m limit, which are also known to be or suspected to be made of these materials.

2.3.4 SMALL OBJECTS

The analysis of EUVE revealed a large number of items that did not meet the 0.25 m minimum length requirement but nonetheless may have a significant probability of reentry. Modeling of examples of these objects, typically made of titanium or stainless steel, revealed that many of them are likely to survive re-entry. The 24 large titanium bolts used to attach the PAP to the PED, the CTA to the PED and MMS, and the slightly smaller bolts that retain the PED modules in the PED and attach the three equipment boxes to the MMS are shown to survive. The largest of these bolts is about seven inches long (0.18 m) by an inch and an eighth in diameter. In addition to these large bolts, it is estimated that there are 3,000 smaller commercial titanium fasteners in the structure, as well as numerous titanium brackets, hinges and other items. As the NSS does not require analysis of these small objects, no results for them are provided in this report.

3. RESULTS

A comprehensive description and illustrations of the break-up sequences assumed for this analysis are found in the following paragraphs. The input conditions and results for each DAS run are shown in Table 2, which also shows if an object is predicted to survive and if not, the calculated demise altitude.

3.1 RUN 1 – INITIAL BREAK-UP

The first run assumed the break-up of the spacecraft into five sub-components, the Payload, the MMS, the PED, the MAPS and the solar panels. The solar panels were assumed to demise immediately and were not modeled. The four modeled components all demised between 77.79 km (MAPS) and 60.54 km (PED); no objects survived to the ground from this initial break-up.

Table 2 DAS Runs for EUVE Components

DAS Run Number	System/Object	Nominal Surface Material	Model Shape	Diameter (m)	Length (m)	Mass (kg)	Synthetic Material	Survive? Yes/No	Demise Altitude (km)
1	EUVE S/C	Aluminum 6061-T6	Cylinder	1.880	3.937	3243.00	N/A	N/A	78.00
1	EUVE Inst	Aluminum 2219-T8	Cylinder	1.702	2.235	1236.95	Inst	No	72.24
2	Spectrometer	Aluminum 2219-T8	Cylinder	1.057	1.575	327.04	SPEC	No	69.14
3	Collimator Back Plate (2)	Molybdenum	Flat Plate	0.235	0.141	1.63	CBP	YES	**0.00**
2	Scanning Telescope	Aluminum 2219-T8	Cylinder	0.584	0.889	117.93	SCAN	No	67.41
2	Telescope Front Cover	Aluminum 6061-T6	Cylinder	0.546	0.064	12.50	COVR	No	69.45
2	Telescope Front Cover Hinge Shaft	SSt #304L	Cylinder	0.028	0.418	1.32	HNG	No	66.01
2	Grapple Fitting	Aluminum 6061-T6	Flat Plate	0.533	0.343	6.27	Grapple	No	69.61
2	Grapple Assembly	Titanium	Cylinder	0.497	0.015	12.70	N/A	**YES**	**0.00**
2	Main Frame	Aluminum 6061-T6	Flat Plate	2.083	1.720	92.11	FRAME	No	72.20
2	Lateral Beam	Aluminum 6061-T6	Flat Plate	1.346	0.244	4.23	N/A	No	66.02
2	Equpt Support Panel	Aluminum 6061-T6	Flat Plate	1.308	0.826	11.11	ESP	No	72.20
2	PAP	Aluminum 6061-T6	Cylinder	1.880	0.076	72.76	PAP	No	71.02
4	Tube Truss (short)	Aluminum 6061-T6	Cylinder	0.086	0.587	2.30	PAPTBS	No	70.30
4	Tube Truss (long)	Aluminum 6061-T6	Cylinder	0.086	1.310	5.12	PAPTBL	No	70.30
4	"V" guide	Aluminum 6061-T651	Cylinder	0.070	0.343	1.29	PAPV	No	69.93
4	Connector carrier	Aluminum 6061-T651	Cylinder	0.448	0.102	1.22	PAPCC	No	71.02
1	PED	Aluminum 6061-T6	Cylinder	1.880	0.579	951.32	PED	No	60.54
5	PED Module (Solar Array Drive)	Aluminum 6061-T6	Cylinder	0.559	0.381	60.78	Pmod	No	55.52
6	Solar Array Drive Interface fitting (2)	Titanium	Cylinder	0.302	0.076	3.34	SAIF	**YES**	**0.00**
6	Solar Array Drive Hub (2)	Titanium	Cylinder	0.267	0.146	13.79	SADA	**YES**	**0.00**
5	Connector Assy PED module	Aluminum 6061-T651	Cylinder	0.356	0.025	1.14	PEDCA	No	60.52
5	Channel Assy Top Cover	Aluminum 6061-T651	Cylinder	0.029	0.483	0.10	PEDCH	No	60.52
5	CTA	Aluminum 2219-T852	Cylinder	1.168	0.152	172.37	CTA	**YES**	**0.00**
1	MMS	Aluminum 2024-T81	Cylinder	1.524	1.397	982.03	MMS	No	67.48
7	Fitting Assy Lower MRS	Aluminum 2024-T351	Cylinder	0.064	0.406	0.87	MRSLF	No	66.98
7	MSS vertical corner beam	Aluminum 7075-T73	Cylinder	0.185	1.087	6.54	MMSCB	No	67.42
7	MSS Top/Bottom Beam	Aluminum 7075-T73	Cylinder	0.088	0.978	2.28	MMSTB	No	67.27
7	MSS tube strut	Aluminum 2024-T3	Cylinder	0.069	1.433	2.18	MMSTS	No	67.27
7	MSS corner bracket	Aluminum 6061-T651	Sphere	0.267		2.03	MMSCR	No	67.42
7	Grapple Extension	Titanium	Cylinder	0.292	0.013	3.78	N/A	**YES**	**0.00**
7	Grapple Assembly	Titanium	Cylinder	0.497	0.015	12.70	N/A	**YES**	**0.00**
7	Torquer Bar Winding	Copper	Cylinder	0.064	1.118	11.34	TorCu	No	61.69
11	Torquer bar iron core	Iron	Cylinder	0.029	1.118	5.68	N/A	**YES**	**0.00**
7	MACS	Aluminum 2024-T81	Cylinder	1.347	0.508	216.82	MACS	No	62.25
8	RWA	Aluminum 2219-T8	Cylinder	0.419	0.127	14.29	RWA	No	57.88
9	RWA rim (4)	SSt #304L	Cylinder	0.113	0.025	2.04	N/A	**YES**	**0.00**
7	MPS	Aluminum 2024-T81	Cylinder	1.347	0.457	281.23	MPS	No	60.90
10	MRS Beam	Aluminum 2024-T351	Cylinder	0.102	1.219	8.07	MRSB	No	59.66
10	Battery Pack (3)	SSt #304L	Cylinder	0.240	0.400	45.78	BATpk	**YES**	**0.00**
7	C&DH	Aluminum 2024-T81	Cylinder	1.347	0.457	200.49	CDH	No	64.25
1	MAPS	Aluminum 6061-T6	Cylinder	0.660	3.048	83.01	MAPS	No	77.79
N/A	Solar Arrays			0.000	0.000	0.00		No	78.00

Notes

1. N/A for a synthetic material shows the object is solid and was modeled using its nominal surface material.
2. Masses are from reference 3 or estimated from material and dimensional data.
3. Dimensions are from references 1, 6, 7, 8, 18 and 19

3.2 RUN 2 – THE EUVE PAYLOAD

As shown in Figure 3, the EUVE payload deck consists of a complex aluminum truss structure to support the telescopes. The structure is mounted to a main frame and also contains equipment support panels, which are all large structures but made lightweight by extensive machining or multipart fabrication. It was assumed for this run that the PAP, which joins the payload to the PED, remained attached to the payload deck following the first break-up. Of particular note for this analysis, the payload deck was also equipped with a large grapple assembly made of titanium. The initial break-up altitude for Run 2 is 72.24 km, the MMS demise altitude from Run 1. All items in Run 2 demised between 72.2 km and 66.02 km except for the titanium grapple assembly, which survived and generated a debris area of 0.67 m^2.

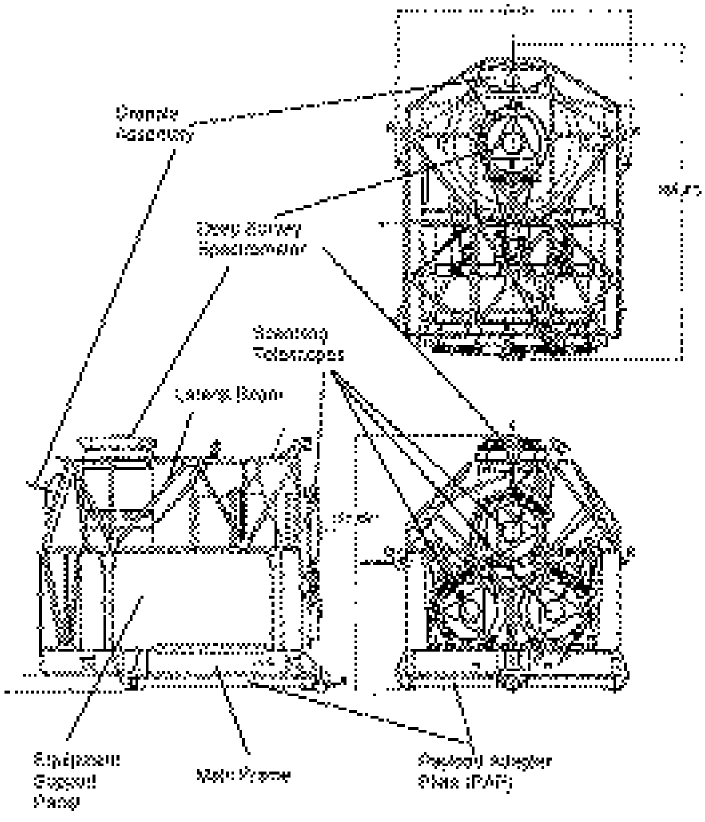

Figure 3. The EUVE Payload Deck [adapted from reference 8, drawing number GE 1466200]

3.3 RUN 3 – THE COLLIMATOR BACK PLATE

The Deep Survey Spectrometer is equipped with two collimators, each of which consists of an assembly of 11 thin molybdenum grids (3 mils thick) sandwiched between 40 mil thick molybdenum picture frame plates. The back plate is the only molybdenum part in the collimator with dimensions that exceed the 0.25 m limit (it is 0.272 m on the diagonal) [reference 18]. The back plate survives generating a reentry debris casualty area of 0.62 m^2. As there are two collimators, the total debris casualty area is 1.24 m^2.

3.4 RUN 4 – THE PAYLOAD ADAPTER PLATE (PAP)

The Payload Adapter Plate (PAP) is a triangular assembly of three long aluminum trusses, three shorter aluminum trusses and three corner brackets as shown in Figure 4. At each corner of the triangle are bolt and floating nut combinations for attachment to the payload on one side and the PED on the other. The bolts are titanium and quite large but are shorter than the 0.25m dimensional limit, as are the floating nuts which are made of stainless steel. Aluminum “V” guides at each corner facilitate alignment of the PAP to the PED. At the center of the PAP is an assembly of three blind-mate connectors that provide electrical interface between the PAP and the PED. These connectors are mounted in an aluminum connector carrier. The PAP was assumed to break free from the payload deck at the demise altitude of 71.02 km found from Run 2. All four items modeled in this run, the long and short trusses, the “V” guides and the connector carrier demised between 71.02 km and 69.93 km.

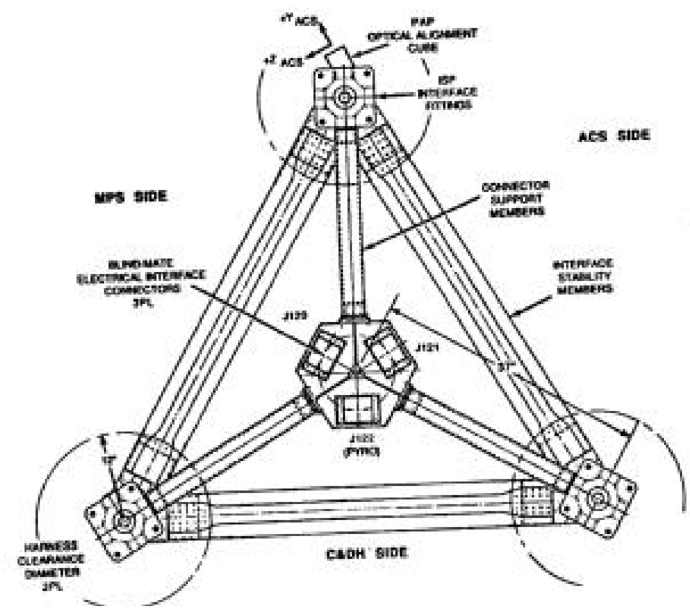

Figure 4. The Payload Adapter Plate (PAP) [from reference 6]

3.5 RUN 5 – THE PLATFORM EQUIPMENT DECK (PED)

The PED consists of a hexagonal parent structure made of lightweight aluminum beams, covered on its top, bottom and portions of its sides with panels consisting of aluminum honeycomb clad with thin aluminum sheets. Into this structure, six similar PED modules are inserted as shown in Figure 5. Each PED module is held in place by the Modular Retention System (MRS), which consists of a large aluminum reinforcing beam and a pair of titanium bolts and accompanying floating nuts. The MRS beams on the PED modules are smaller versions of those used on the MPS, MACS and C&DH boxes mounted to the MMS. The MRS beam for the MMS was modeled in Run 10 for the MMS and found to easily demise so the smaller PED version was not modeled. The PED modules are electrically connected using two large connectors in an aluminum housing. The PED modules are guided into the PED by aluminum channels. For this run, the Circular Transition Adapter (CTA) was assumed to have remained attached to the PED during the initial break-up and to become free falling after the demise of the PED. The modules, the connector assembly and a guide channel were all found to demise between 60.52 km and 55.52 km. The CTA survives, generating a reentry debris casualty area of 1.33 m^2. Note, as the CTA contained two of the torquer rods, these are assumed to have survived as part of the CTA and to have contributed to its debris field and are not modeled separately. Based on the results of Run 11 (see Section 3.11), if these torquer rods fell independently from the CTA, their iron cores could be expected to survive and generate an additional 2.20 m^2 of debris casualty area.

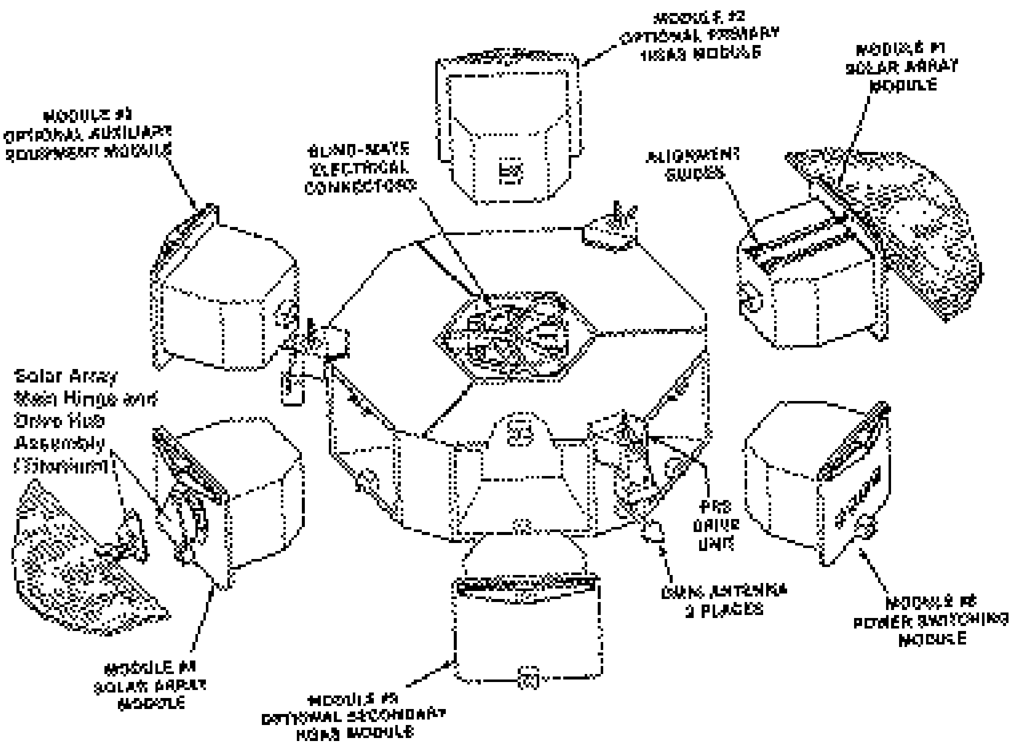

Figure 5. The Platform Equipment Deck (PED), with the modules that fit inside it [adapted from reference 6]

3.6 RUN 6 –THE SOLAR ARRAY PED MODULES

The two PED modules that contain the solar array drives are each equipped with a large titanium support hub to which the heavy-duty titanium main hinge assembly called an interface fitting is attached (see Figure 5). These items were not assumed to free-fall until their parent PED module demised at 55.52 km. Both items survived generating debris areas of 0.65 m^2 for each hub and 0.61 m^2 for each interface unit; a total debris area of 2.5 m^2 for both solar array modules.

3.7 RUN 7 – THE MULTI-MISSION SPACECRAFT (MMS)

The Multi Mission Spacecraft (MMS) consists of the Module Support Structure (MSS) to which three large equipment boxes are attached as shown in Figure 6. The MSS is a triangulated truss and beam structure made mostly of aluminum. The MSS is assumed to break into its component parts as the MMS demises. Therefore, this run models free-falling MSS beams, struts, and corner brackets, as well as the MACS, MPS and C&DH modules. There is one torquer bar 44 inches long, 2.5 inches in diameter and weighs 25 pounds mounted in the MMS. It consists of a glass fiber casing, around a pair of copper wire windings 0.27 inches thick on top of a ferromagnetic core, 1.13 inches in diameter. For this analysis, the glass fiber casing is assumed to demise as soon as it is exposed by the demise of the MMS; only the copper windings are modeled in this run. The copper windings were found to demise at 64.42 km, necessitating a run to analyze the ferromagnetic core (see 3.11, Run 11). In addition, the MSS has a large titanium grapple supported by a large titanium grapple extension attached to one corner. All components analyzed for this run demised between 67.42 km and 60.90 km except for the grapple extension and assembly which both survived. The calculated debris area is 0.55 m^2 for the extension and 0.67 m^2 for the grapple assembly, 1.22 m^2 total.

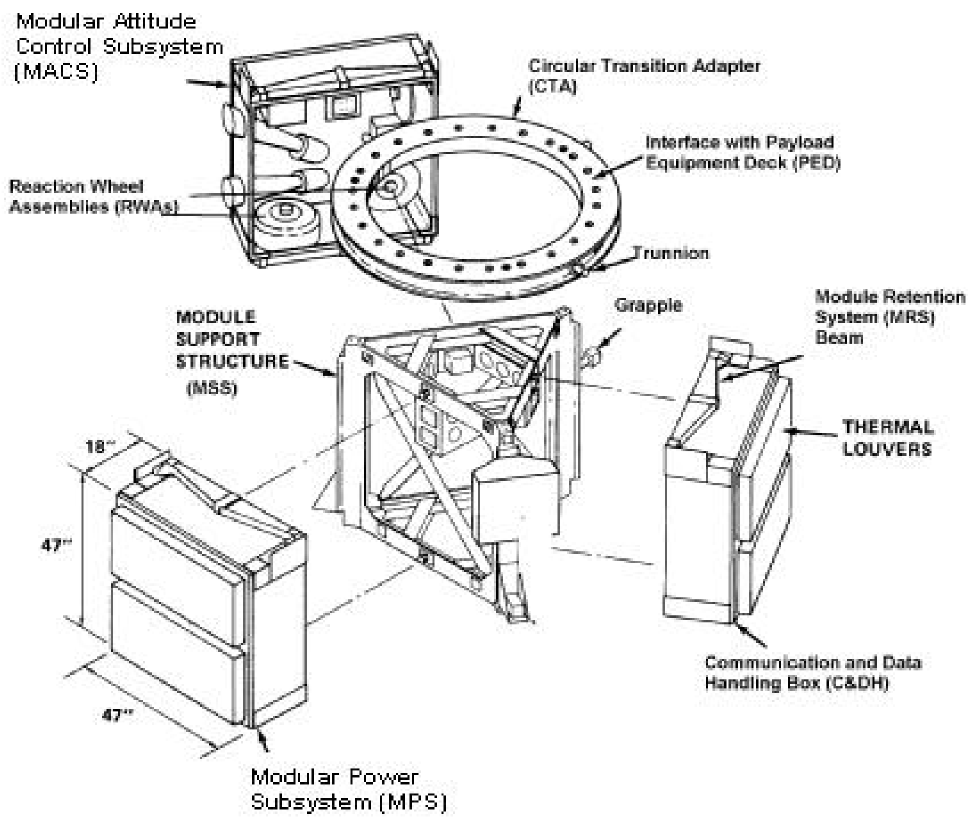

Figure 6. The Multi-mission Modular Spacecraft (MMS) [adapted from reference 13]

3.8 RUN 8 – THE MODULAR ATTITUDE CONTROL SYSTEM (MACS)

The MACS contains four Reaction Wheel Assemblies (RWAs) each of which consists of an aluminum housing containing a momentum wheel. The RWAs were modeled because it was suspected that the steel rims on the wheels would survive. The RWAs were supplied as assemblies by a sub-contractor and the actual drawings could not be located. The sub-contractor was able to supply envelope dimensions and mass information. This run showed that the assemblies demised at 57.88 km, necessitating a run to analyze the rims.

3.9 RUN 9 – THE RIMS OF THE REACTION WHEELS

A drawing for a reaction wheel rim was found for the generic, Explorer Platform on which the EUVE spacecraft is based. This rim drawing was from the correct manufacturer, so the dimensions of this drawing, modified to match the EUVE mass data were used for this run. The rim survived, generating a debris area of 0.45 m^2 for each wheel, a total of 1.80 m^2 for all four wheels.

3.10 RUN 10 – THE MODULAR POWER SUPPLY (MPS) BOX

The MPS box contains three large nickel cadmium battery packs rated at 50 ampere hours. Each pack consists of 22 individual steel-cased, hermetically-sealed cells mounted together in two rows of 11 cells as shown in Figure 7. The 22 cells are held together as a unit by four long clamp bolts and two clamp plates. The mass and dimensional details for the cells are known precisely from the manufacturer's documentation [reference 19] but the details of the assembled packs are only known from photographs and sketches. Following the CGRO methodology, the batteries were assumed to free-fall in the 3 packs, once the MPS demised. The battery packs survived generating debris areas of 0.840 m^2 per battery for a total of 2.52 m^2 for three.

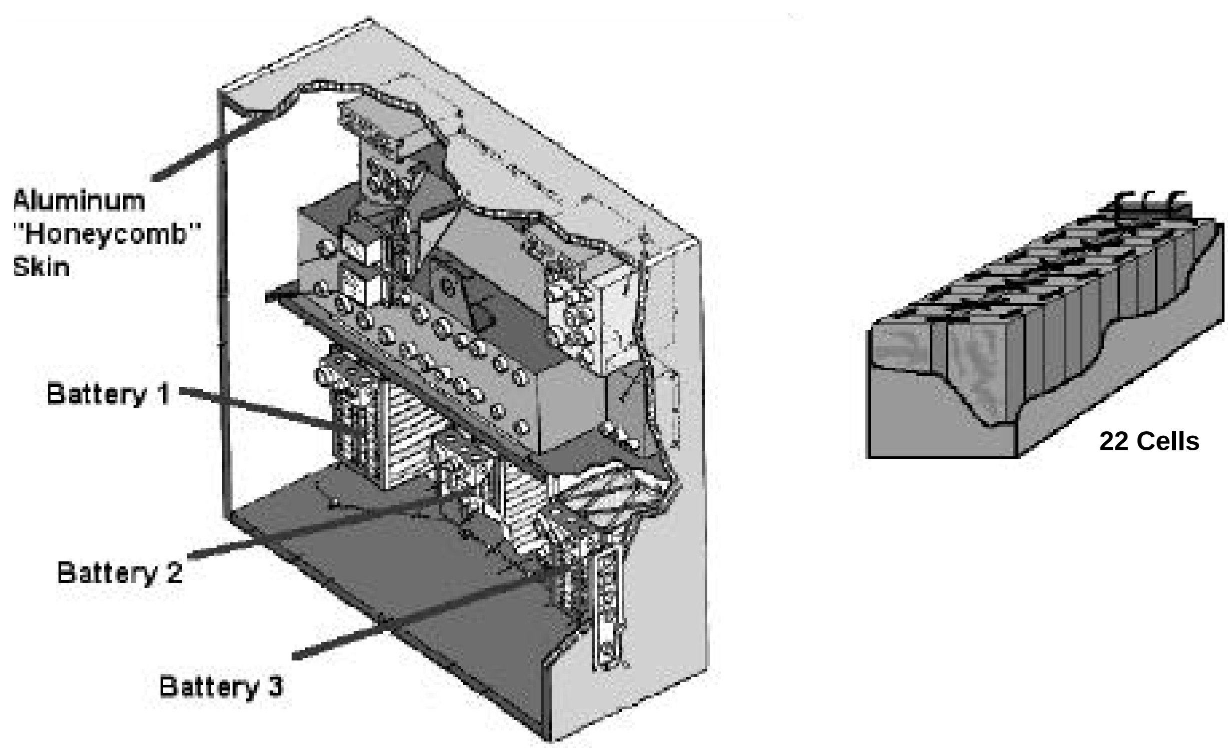

Figure 7. The Modular Power Subsystem (MPS) box showing the location of the battery packs. A schematic of a single battery pack is shown on the right [adapted from reference 20].

3.11 RUN 11 – THE TORQUER BAR CORE

The torquer bar core was shown to be exposed at an altitude of 64.42 km when the copper windings demised in Run 7. The manufacturer considers the core material to be proprietary so it was modeled as iron for this analysis. The core diameter used for the model was slightly larger in diameter than the actual part, as DAS will not accept length to diameter ratios exceeding about 40 times and the core is right at this limit. As modeled, the core survives generating a reentry debris casualty area of 1.10 m^2.

3.12 THE MODULAR ANTENNA POINTING SYSTEM (MAPS)

The MAPS was supplied as an assembly by a sub-contractor and the detailed drawings have not been located. The information, sketches and photographs that were found show a lightweight structure with no obvious candidate components likely to survive reentry. Therefore, the MAPS was assumed to demise completely at 77.79 km.

3.13 TOTAL REENTRY DEBRIS CASUALTY AREA FOR EUVE

The **total reentry debris casualty area** calculated for EUVE in accordance with NASA Policy Directive NPD 8710.3, is **12.41 m^2**. Table 3 provides a summary for all objects predicted to survive. Figure 8 provides a pictorial summary of the complete break-up model for EUVE, showing the objects that demise and those that survive.

Table 3. Summary of EUVE Components Predicted to Survive Reentry

RUN#	Description of Surviving Object	Principal Constituent Material	Debris Casualty Area for Object (m^2)	Number of Examples of the Object	Total Mass of Object(s) (kg)	Total Debris Casualty Area (m^2)
1	N/A					0.00
2	Grapple Assembly	Titanium	0.67	1	12.7	0.67
3	Collimator Backplate	Molybdenum	0.62	2	3.26	1.24
4	N/A					0.00
5	Circular Transition Adapter	Aluminum	1.33	1	172.37	1.33
6	Solar Array Drive Hub	Titanium	0.65	2	27.58	1.30
6	Solar Array Drive Interface Unit	Titanium	0.61	2	6.68	1.22
7	Grapple Extension	Titanium	0.55	1	3.78	0.55
7	Grapple Assembly	Titanium	0.68	1	12.7	0.68
8	N/A					0.00
9	Reaction Wheel Rim	Stainless Steel	0.45	4	8.16	1.80
10	Battery Pack	Stainless Steel	0.84	3	137.34	2.52
11	Iron Core of Torquer Rod	Iron	1.10	1	5.68	1.10
TOTALS				**18**	**390.25**	**12.41**

EUVE DAS MODEL

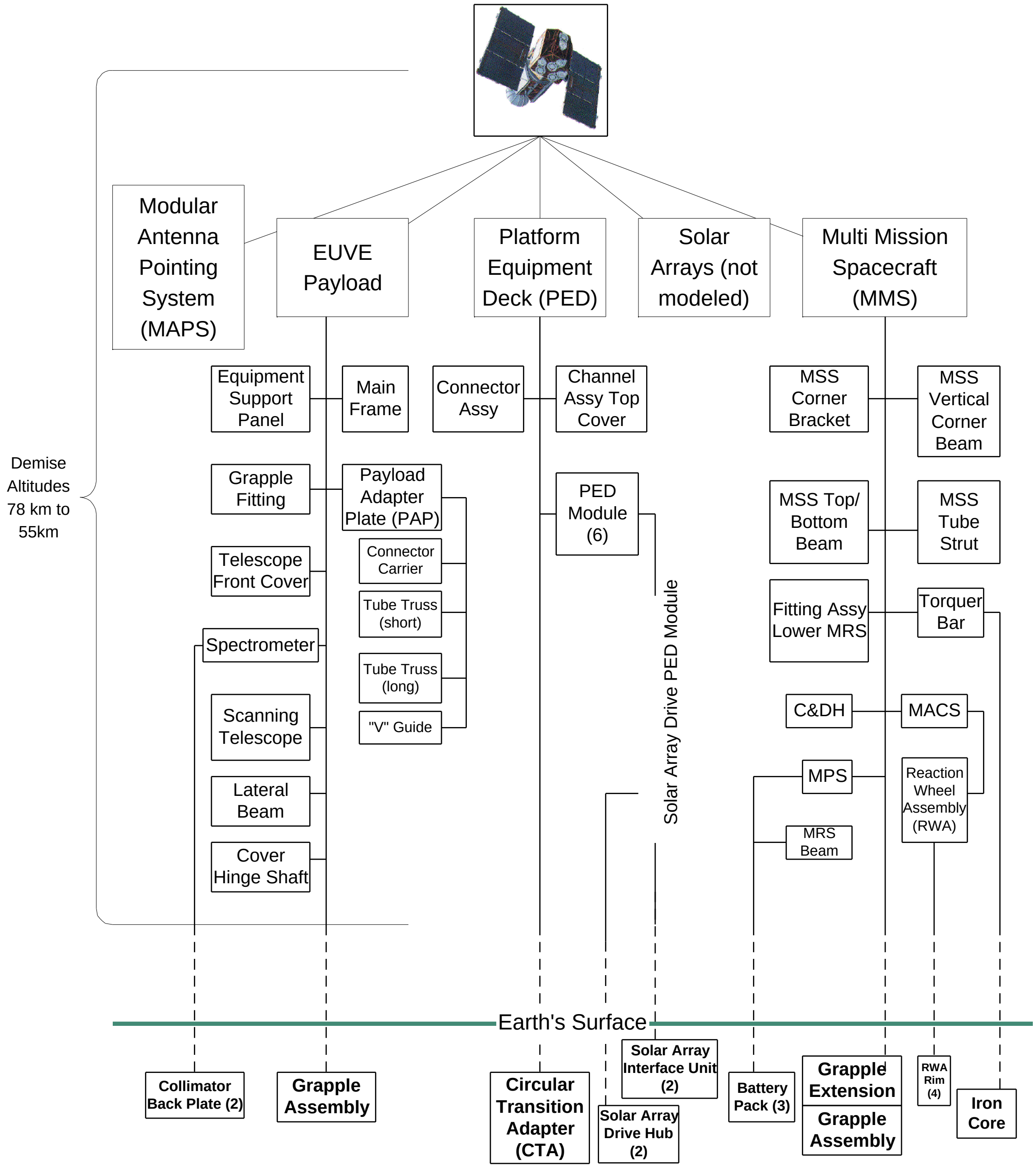

Figure 8. A pictorial summary of the break-up of EUVE. Objects that survive reentry are shown below the line denoting the earth's surface, with the remaining objects in the approximate order they demise.

4. DISCUSSION OF METHODOLOGY

Throughout this analysis situations were encountered where it was necessary to make an assumption, or choose between options. The most common situation involved the shape to use for modeling an irregular object. Experimentation was performed to evaluate the impact of a number of choices. It was found that the best correlation to similar objects modeled for the CGRO reentry analysis was achieved using cylinders. Therefore, objects were transformed into cylinders whenever possible. This transformation often involved severe distortion of the object. The other common situation involved the estimation of mass.

Wherever possible, the mass used for analyzing an object was taken from the mass properties analysis report but if this information was not available it was necessary to estimate the mass. This could be difficult given the extensive machining and complex 3-dimensional nature of many of the objects. There were also complications such as the filling of hollow beams with lightweight aluminum honeycomb material. Numerous assumptions were made regarding the amount of material removed by drilling or machining, and the extent of fill with honeycomb.

In the section describing the various DAS runs, the scenario used for the break-up of the EUVE structure is described in detail. Every one of these runs involved choices and assumptions regarding which part broke away from which, when and in what manner.

Any of these assumptions or choices has the potential to significantly impact the analysis results. There can be a trickle down impact. A change in the demise altitude of a major component could in turn affect the demise altitude of one of its sub-components and so on, possibly resulting in the survival of a component that would demise under a different scenario. Likewise, assumptions about the order in which the structure disintegrates and choices made in modeling multi-part objects affect the results.

In general, a conservative approach was taken when making assumptions or selecting options. Masses and areas were generally overestimated. In the end, the results seem reasonable. All aluminum objects except one demised. That object, the Circular Transition Adapter was modeled using the mass properties report value for its mass, which probably included many non-aluminum objects such as titanium trunnions and iron-cored torquer rods. Most of the other surviving objects were made of titanium, with one each made of iron, stainless steel and molybdenum. These materials all have high melting points and other properties that make them likely to survive.

5. CONCLUSIONS

This report has presented a reentry debris analysis for the Extreme Ultraviolet Explorer (EUVE) spacecraft performed using Debris Analysis Software (DAS) in accordance with NASA Policy Directive NPD 8710.3, NASA Policy for Limiting Orbital Debris Generation, and NASA Safety Standard NSS 1740.14, “Guidelines and Assessment Procedures for Limiting Orbital Debris”. From this analysis it is estimated that, if the Extreme Ultraviolet Explorer (EUVE) spacecraft is allowed to reenter without interference, it will generate a total reentry debris casualty area of 12.41 m^2 from the survival of 18 individual objects. This exceeds the 8 m^2 limit specified in NASA Safety Standard NSS 1740.14, “Guidelines and Assessment Procedures for Limiting Orbital Debris”. The 12.41 m^2 debris casualty area represents a risk of approximately 1 in 5400 (0.019%) for causing a human casualty within EUVE’s ground track. If this is considered unacceptable, then NASA Policy Directive NPD 8710.3, NASA Policy for Limiting Orbital Debris Generation, requires the establishment and implementation of additional debris mitigation measures.

It can also be concluded from this study that it is only necessary to model the largest aluminum objects for a reentry analysis but imperative to identify all titanium, steel and other high melting point components that exceed the 0.25 m limit.

ACRONYMS AND ABBREVIATIONS

CGRO	Compton Gamma Ray Observatory
C&DH	Communications and Data Handling
CTA	Circular Transition Adapter
DAS	Debris Analysis Software
DOS	Disk Operating System
EUVE	Extreme Ultraviolet Explorer
MACS	Modular Attitude Control Subsystem
MAPS	Modular Antenna Pointing System
MMS	Multi-mission Modular Spacecraft
MPS	Modular Power Subsystem
MRS	Module Retention System
MSS	Module Support Structure
ORSAT	Object Reentry Survival Analysis Tool
PAP	Payload Adapter Plate
PED	Platform Equipment Deck
RWA	Reaction Wheel Assembly

ACKNOWLEDGMENTS

I rapidly realized that success in this analysis would depend on input from a large number of people. The relevant documentation resided in several separate libraries whose existence and importance were learned from personal contacts; no central record for EUVE documentation was ever located. I want to thank Tom Smith of EER Systems, Jim Chipouras and Bill Gallagher of Computer Sciences Corporation, and Justin Ward and Kevin Carmack of Orbital Sciences Corporation for their patience and assistance in tracking down the documents. Also, I found there was no substitute for direct contact with people who helped build or operate EUVE. My thanks to, Joe Whitacre, Ruth Cholvibul and Steve Pataki of Orbital Sciences Corporation (Fairchild when EUVE was built), and Lee Niemeyer, Frank Cepollina, Nelson Rubin and Jeff Stuart of NASA GSFC. Finally, I needed extensive assistance in developing the reentry model and running and manipulating the Debris Analysis Software. I want to thank Eric Holmes of NASA GSFC, Nick Johnson of NASA JSC, and Robin O'Hara and Bill Rochelle of Lockheed Martin at JSC for their willing and patient support and valuable suggestions.

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